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ELECTRON AVALANCHE MODEL OF DIELECTRIC-VACUUM SURFACE BREAKDOWN

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Abstract

The model assumes that an "initiating event" results in positive ions on the surface near the anode and reverses the direction of the normal component of electric field so that electrons in vacuum are attracted to the dielectric locally. A sequence of surface electron avalanches progresses in steps from the anode to the cathode. For 200 kV across 1 cm, the spacing of avalanches is predicted to be about 13 microns. The time for avalanches to step from the anode to the cathode is predicted to be about a ns.

Introduction

We are concerned with a geometry like that shown in Fig 1. With no charge on the dielectric, surface electron avalanches cannot occur because En (the component of electric field normal to the interface) has the direction to push electrons from the dielectric to the vacuum. In order for surface avalanching to start, an "initiating event" must occur. This results in positive charge on a local region of the surface and reverses the sign of En locally. Fig 1 depicts two types of initiating events. Anode initiation is shown on the left. A whisker or other defect on the dielectric surface results in ionization of dielectric atoms. The resulting electrons are collected at the anode and positive charge is left on the surface. This event is most likely in the enhanced field region near the anode triple junction (ATJ). Anode initiation usually results in an "anode tree" damage pattern. A possible model for cathode initiation is depicted on the right in Fig 1. A defect on the cathode results in electron emission. The electrons cross from the cathode to the anode, backscatter from the anode and spray on the dielectric surface near the anode. Dielectric atoms near the surface are ionized, the resulting electrons are collected at the anode and positive charge is left on the interface. Cathode initiation doesn't produce a damage pattern. Anode initiation results in the anode tree damage pattern which is only about a micron wide near the anode. Cathode initiation starts from a wider region.

Fig 2 shows an example of an anode tree damage pattern. Previously, anode initiated surface breakdown has been modeled as a sequence of solid dielectric breakdowns progressing from the anode to the cathode (1). The present model involves a sequence of surface electron avalanches progressing from the anode to the cathode. The damage pattern suggests that:

1) The avalanches start near the anode.
2) Avalanching occurs on or near the surface (within about 1 micron).
3) After a particular avalanche dies out, a new one starts about 10 to 20 microns away.

Measurements also show that:

4) Avalanches progress from the anode to the cathode in a very short time, ($\leq$3ns).

A successful model should predict these characteristics

Model Equations for Anode Tree Breakdown

Fig 3 depicts a secondary electron orbit with initial momentum perpendicular to the surface and with En pushing the electron toward the dielectric. Boersch, Hamisch and Erlich analysed this motion in 1963 assuming the field components to be constant over the small dimensions of the orbit (2). Their equations are:

$$U_0 = eE_n v_0 \qquad \text{(esu)}$$

$$v_0 = \frac{1}{2}\frac{eE_n}{m}(t/2)^2$$

$$l = \frac{1}{2}\frac{eE_t}{m}t^2$$

$$U = U_0 + elE_t$$

Uo is the initial and U is the final kinetic energy, e and m are the electron charge and mass. t is the time . Et is the tangential component of E-field.
Starting from these equations we derive:

$$l = 2U_0\frac{E_t}{E_n^{\ 2}}$$

$$U = U_0(1+2\frac{E_t^{\ 2}}{E_n^{\ 2}})$$

$$to = 4.78*10^{-12}\frac{\sqrt{U_0}}{E_n}$$

where the units are now microns, ev and volts/micron. to is the orbit time in sec. The factors of 2 occuring in the equations for l and U are the result of an original factor of 4 being decreased by ½ as a result of averaging cos^2 over an isotropic distribution of angles. We used Uo=2 ev. A single electron is released at uo. n[u] electrons move in the negative u direction and an equal number of immobilized positive ions are distributed at the positions where they were formed.

$$-\frac{dn}{du} = n\frac{(\sigma-1)}{l}$$

d=-dn/du

$$Et_i = Etp_i - 1.44*10^{-3}\frac{2}{\varepsilon+1}\sum_j \frac{\Delta d_j}{(\Delta i - \Delta j)^2}$$

$$En_i = Enp_i \text{-} 1.44*10^{-3}\frac{2}{\varepsilon+1}\sum_j \frac{\Delta d_j v_c}{[(\Delta i-\Delta j)^2+v_c{}^2)]^{3/2}}$$

$\sigma[U]$ is the secondary electron coefficient. d is the line density of positive ions. Eti and Eni are the fields at ui, (the position of the electrons for the ith step). Etp and Enp are the fields before the avalanche starts calculated with OMNITRAK. The remaining terms give the fields at ui due to the positive ion distribution generated in previous steps of the present avalanche. j=i would result in a zero denominator. The sums over j are cut off at j=i-k where kΔ is the cut-off distance from the head of the avalanche. We have used kΔ= one micron, corresponding to one micron transverse size of the avalanche. ε is the dielectric constant (we used 2.8). Δ is the step size in microns. We used .01 microns. Using .001 microns only changes n by a few percent. v_c is the average distance of the charge inside the dielectric. The images of the ion charges in the anode are neglected because they are much farther from u than the nearest ions. The equations are solved in Mathematica using a "do loop" and taking steps in the negative u direction.

Fig 4 shows our model geometry with 45 degree interface slope. Also shown are the locations of charge boxes which are initially empty. Charge is put in box 1 simulating the result of an anode initiating event. Charge is placed in boxes 2, 3 and 4 as a result of stepping electron avalanches. In order to get En at the surface to change sign 10 to 20 microns upstream of the charge location, we have modeled the charge as buried at an average depth of 1 micron in the dielectric. (The average depth on Fig 1 is 0.5 micron but we read En at 0.5 micron into the vacuum)

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Results

Fig 5 shows the fields near the ATJ with no charge on the dielectric. OMNITRAK cannot give En exactly on the surface. These fields are on a line in vacuum located 1 micron from the dielectric. Each field calculation involved calculating the fields in seven different meshes, starting with a mesh that included both electrodes and reducing the mesh size and grid size in steps of about a factor of two and matching the boundary field of a mesh to the field of the previous mesh. The final grid size was 0.5 micron.

To allow the first avalanche to occur, 0.3 x10^8 positive charges were put in box number 1 on Fig 4, simulating the result of an " initiating event". The field was calculated and an avalanche was run in the field. Assuming all the electrons were collected at the anode, this resulted in about 2x10^8 positive ions and these were put in box number 2. The field was calculated and another avalanche was run resulting in about 2x10^8 ions which were put in box 3. The field was calculated and avalanches were run resulting in about 3x10^8 ions at position 4. We present the fields between cases 3 and 4 and the avalanches at 4. Figs 6 and 7 show the fields in the region of avalanche growth. Note that Et is about 15 to 30 times stronger than for the case of no charge. Fig 8 shows the normalized σ curve. This is for the measurements given in ref 3 for 80 degree angle of incidence on plastics.

σ max of 3 was used and U max was 250 ev. Fig 9 shows Et vs u for avalanches starting at three different values of uo, 50,44, and 40 microns. As the electron bunch moves to the left, the field at the center of the bunch is that shown on Fig 6 until the field of the ions produced by the present avalanche turns on and reduces the field to zero. The run is stopped at this point because the simple equations used can't cope with a negative Et. Fig 10 shows l vs u for the same cases. l starts out large (1 or 2 microns) because En is small and the orbit time is long. When Et drops toward zero, l becomes small. Fig 11 shows U vs u. U is proportional to the product of the local l and the local Et. It collapses when Et collapses. σ is shown on Fig 12 and it drops when U drops. The exponential growth rate $(\sigma - 1)/l$ is shown on Fig 13. It is initially small because l is large. It increases as l decreases at constant σ and then drops when $(\sigma - 1)$ drops to 0. Fig 14 is an overlay of the different avalanches to show the step size (about 13 microns).

To calculate the time for an avalanche, orbit lengths were connected together to fit in the distance between u = 44 and 40 microns:

{0.667339,0.572632,0.502091,0.443934,0.397849,0.361471,0.332526,0.305045,0.270489,0.200356}.

The times for each orbit were calculated:

{1.15752, 1.0347, .9383, .85563, .78757, .73213, .6875, .64796, .6126, .58169}x10^-13

The sum is 8.04x10^13 sec. If 1000 avalanches each 10 microns long are required to bridge from the anode to the cathode, then the time would be about 1 ns.

Discussion

Most of the results of the calculations can be understood by noting the u-dependence of Et and En and the dependence of l and U upon Et and En.

Avalanche growth only occurs over a restricted range of u, from u= 54 to 31 microns in the present example. As u is decreased, Et/En decreases. This causes l and U to decrease. The egr goes to zero where sigma –1 goes to zero. This occurs at u=31 microns with the field of the ions of the present avalanche switched off. With these sum terms on, the egr goes to zero at larger u because Et is decreased.

We modeled the avalanche steps as purely in the u direction. The ion field is about 15 to 30 times stronger than the no-charge field, so the steps could have a z-component.

In assigning the charges in the boxes on Fig 4, it was assumed for simplicity that the electrons were collected at the anode. Actually, as Et drops to zero (see Fig 9), it is more likely that part of the electrons are removed to the anode and part are trapped by the ions. We are working on a particle-in-cell model of the stepping avalanches. The E field is updated for each step of the calculation, so this calculation should be more accurate as Et changes sign.

Once the initiating event has occurred, the surface avalanching is probably unstoppable. The best hope for increasing the breakdown voltage may be to prevent the initiating event. In the case of cathode initiation, it may be possible to change the geometry so as to prevent the backscattered electrons from hitting the anode. Eliminating dielectric surface imperfections near the anode would inhibit anode initiated breakdown.

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References

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(2) Boersch, Hamisch and Ehrlich, Zeitschrift fur angewandte physik,V15 (6), 1963, p 518
(3) Kai-Yueh Yang and R. W. Hoffman, Electron Yields and Escape Depths from Kapton and Teflon, Surface and Interface Analysis, Vol 10, 121-125, (1987)

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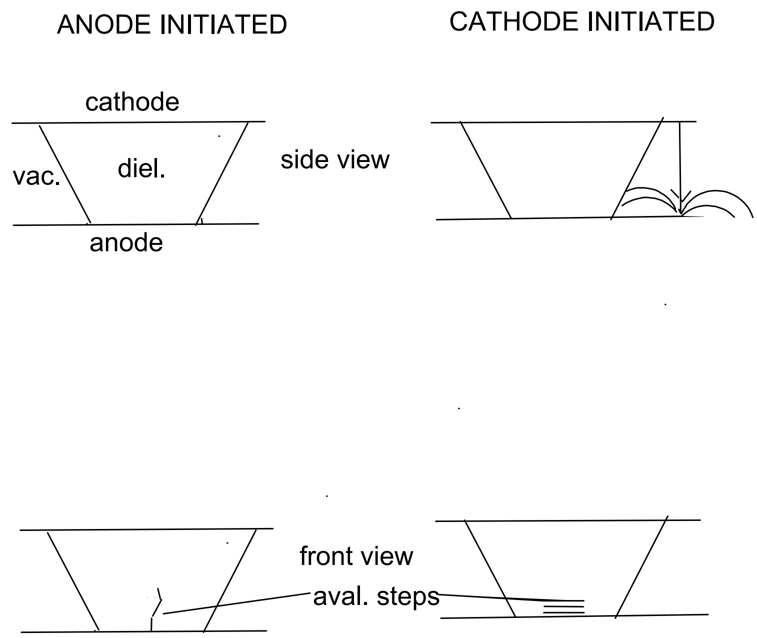

Fig 1 Anode Initiated and Cathode Initiated Breakdown

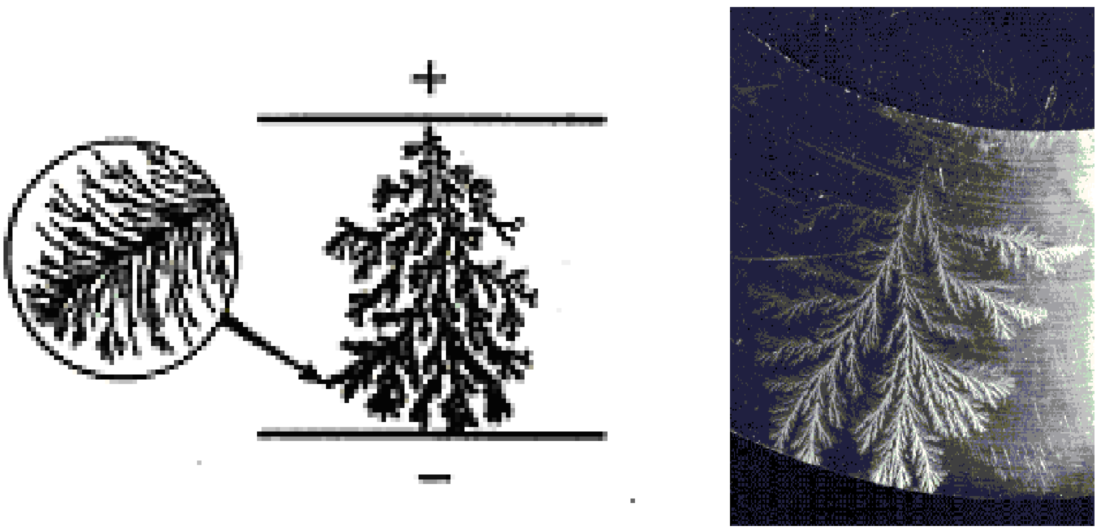

Fig 2 Anode Tree Damage Pattern

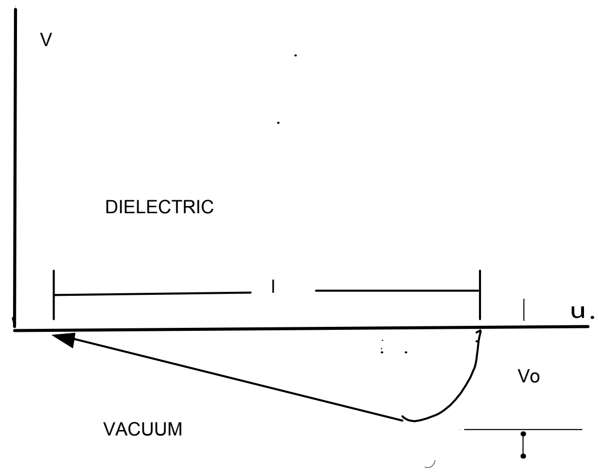

Fig 3 Secondary electron orbit

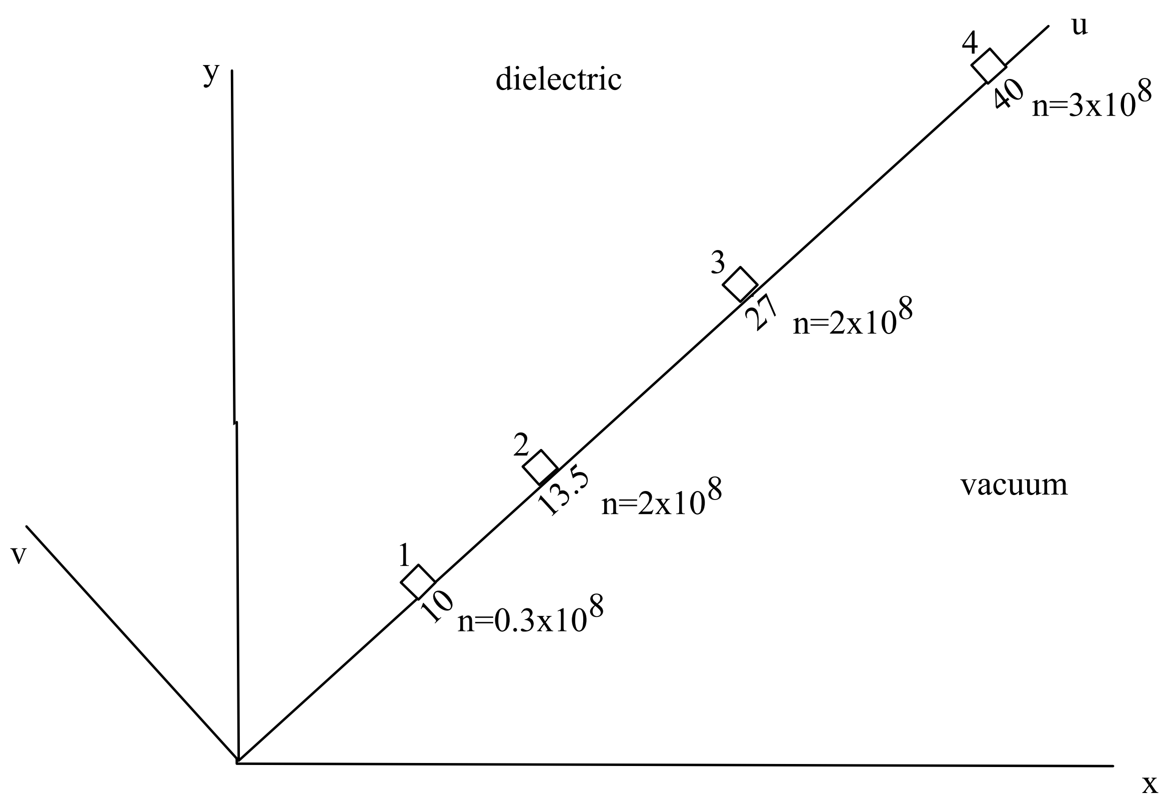

Fig 4 Geometry and location of charge boxes, z is directed into page, boxes are 1 micron cubes., anode-cathode distance=1cm, Vo=200 kV

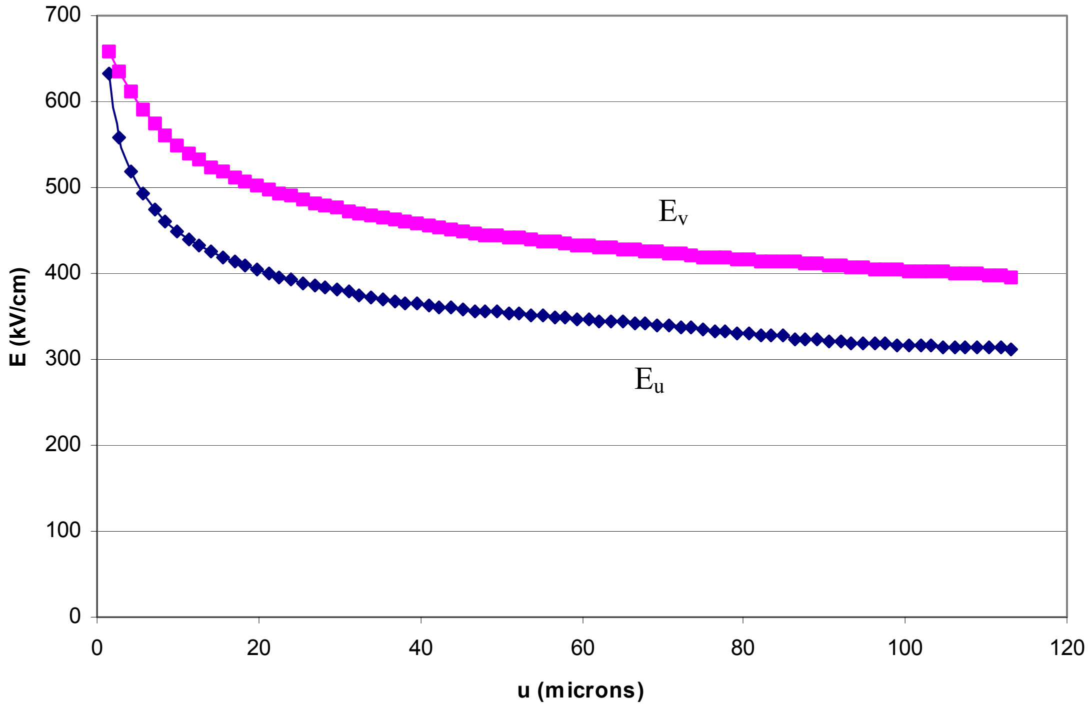

Fig 5 No- charge fields, v = -1 micron

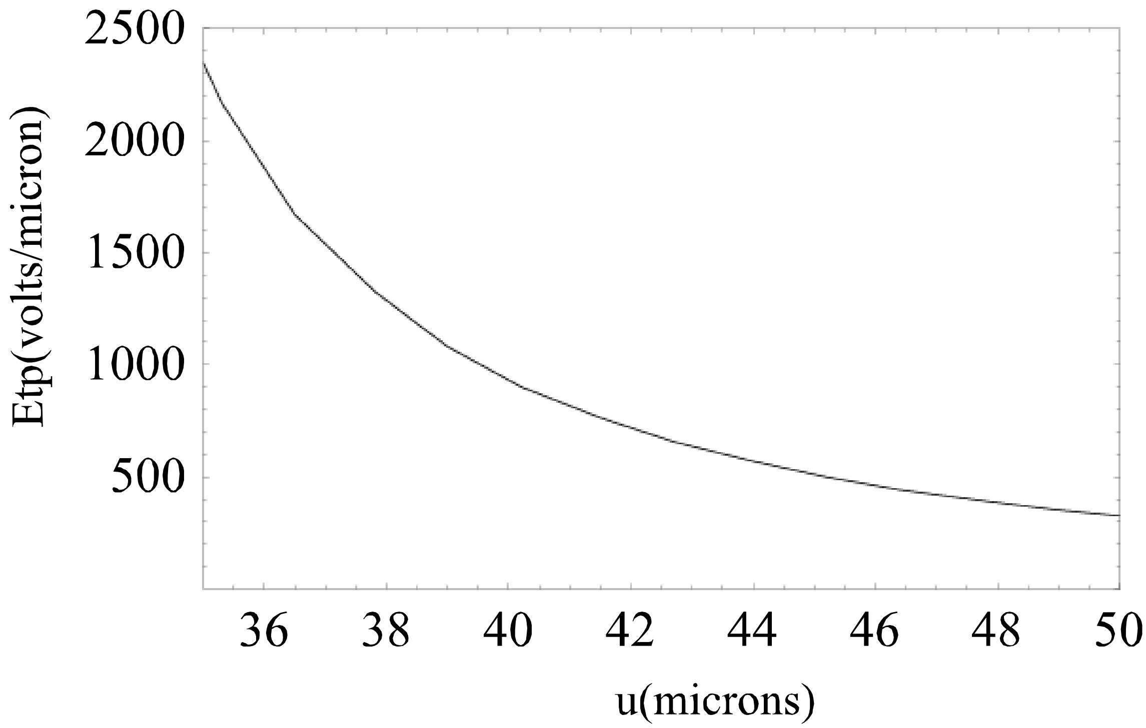
2500
2000
1500
1000
500
Etp(volts/micron)
36
38
40
42
44
46
48
50
u(microns)

Fig 6 Etp vs u

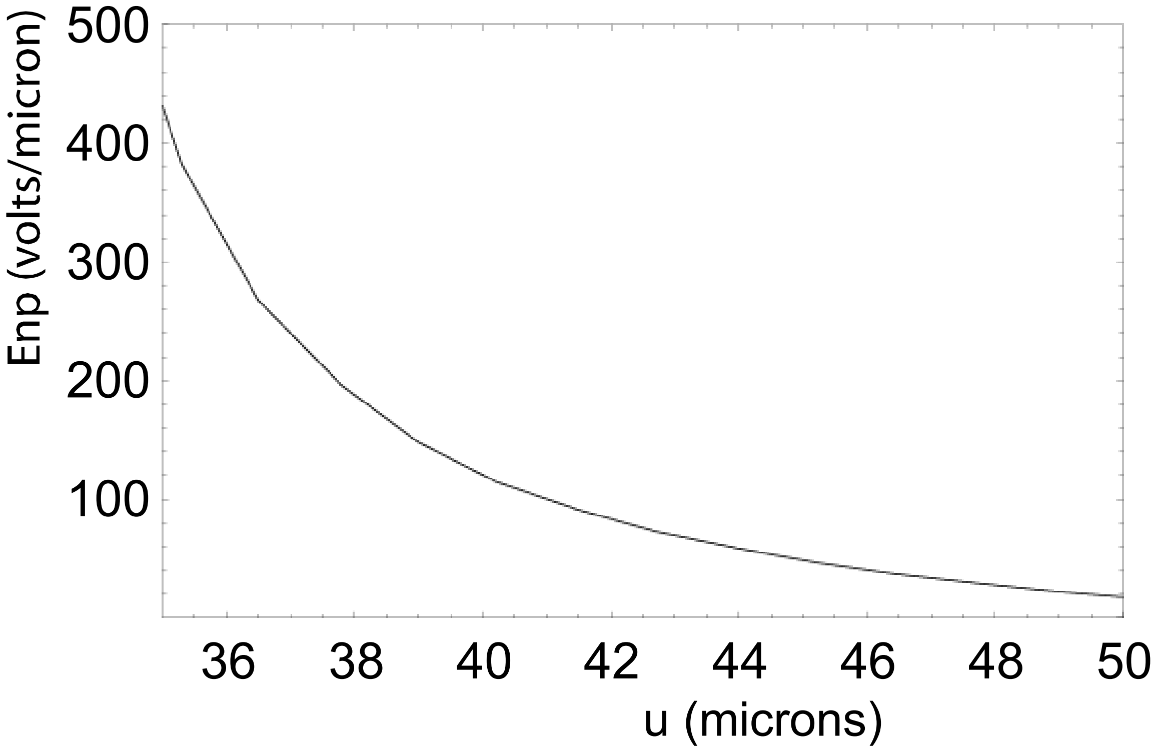
Enp (volts/micron)
500
400
300
200
100
36
38
40
42
44
46
48
50
u (microns)

Fig 7 Enp vs u

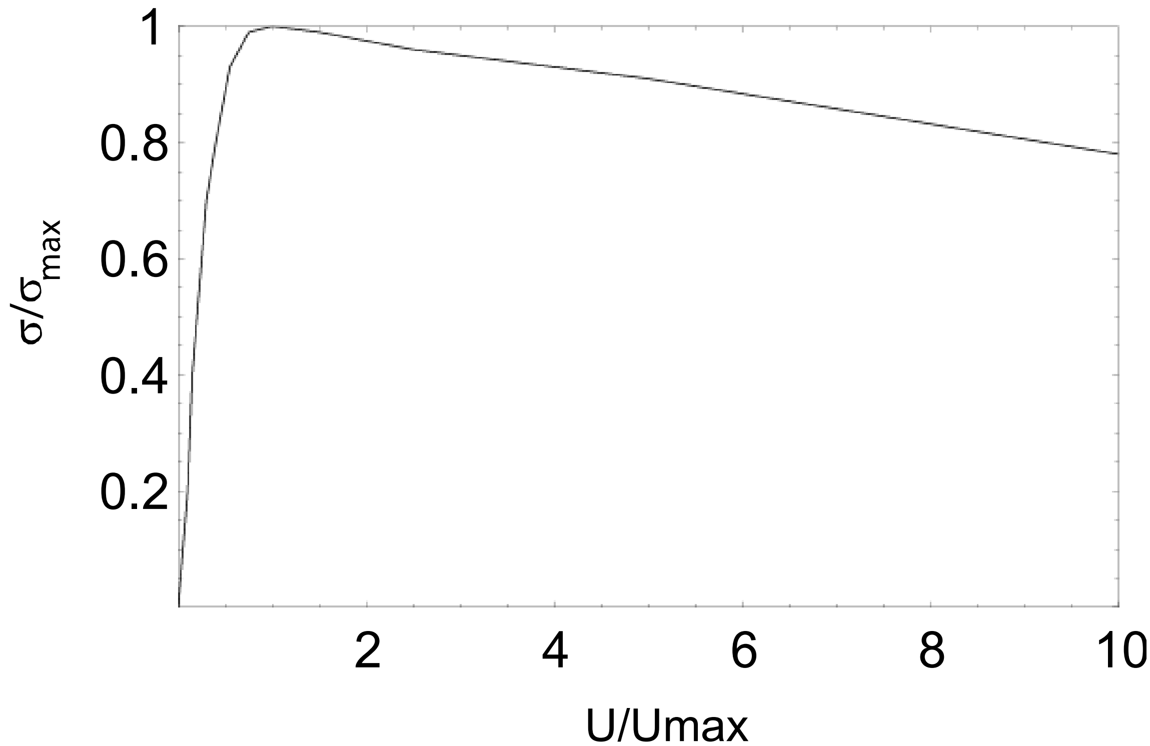

Fig. 8 Normalized σ curve

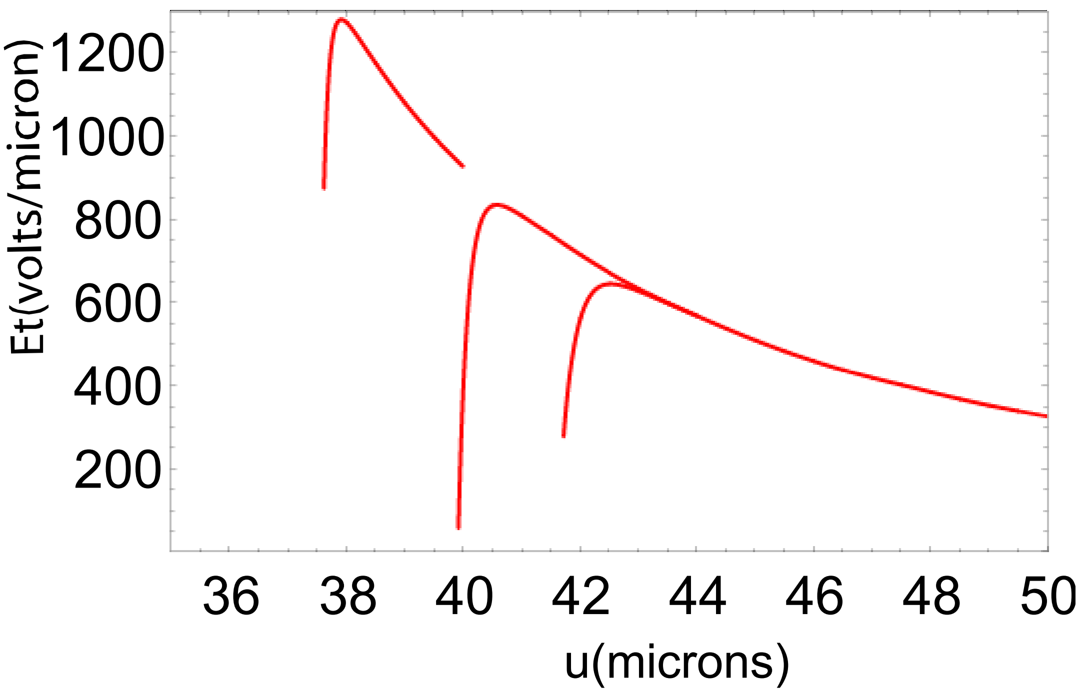

Fig 9 Et vs u, uo=50,44 and 40 microns

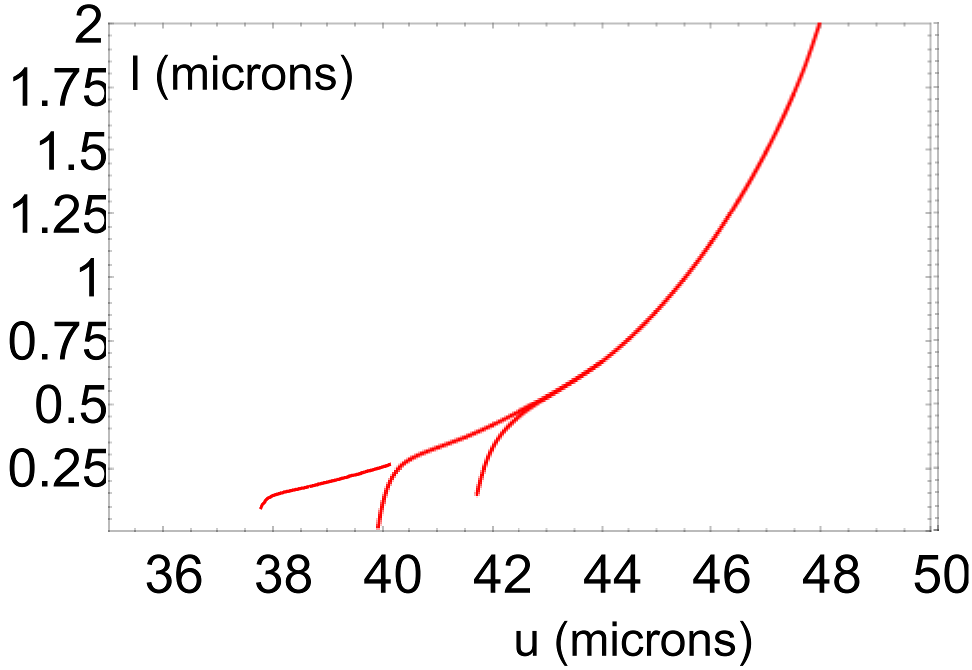

Fig 10 l vs u, uo= 50, 44 and 40 microns

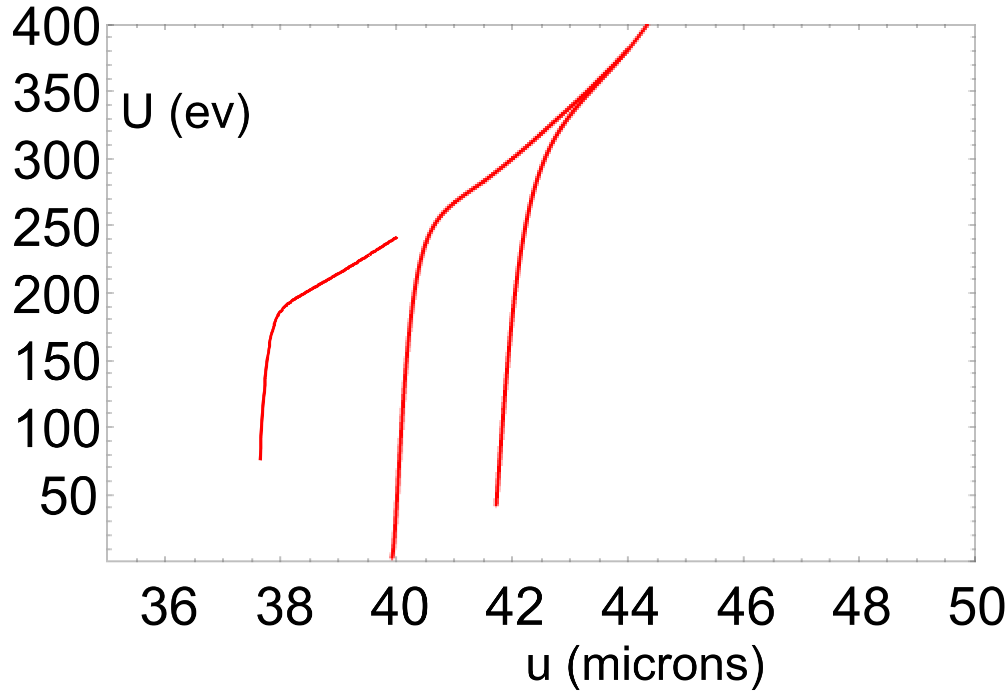

Fig 11, U vs u, uo= 50, 44 and 40 microns

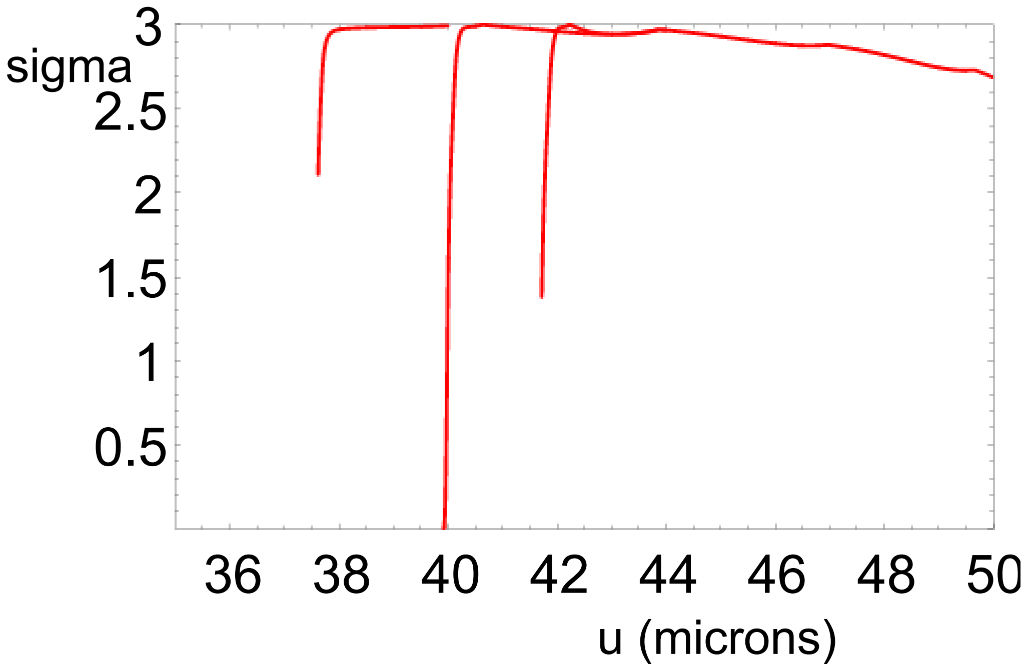

Fig 12 sigma vs u, uo= 50, 44 and 40 microns

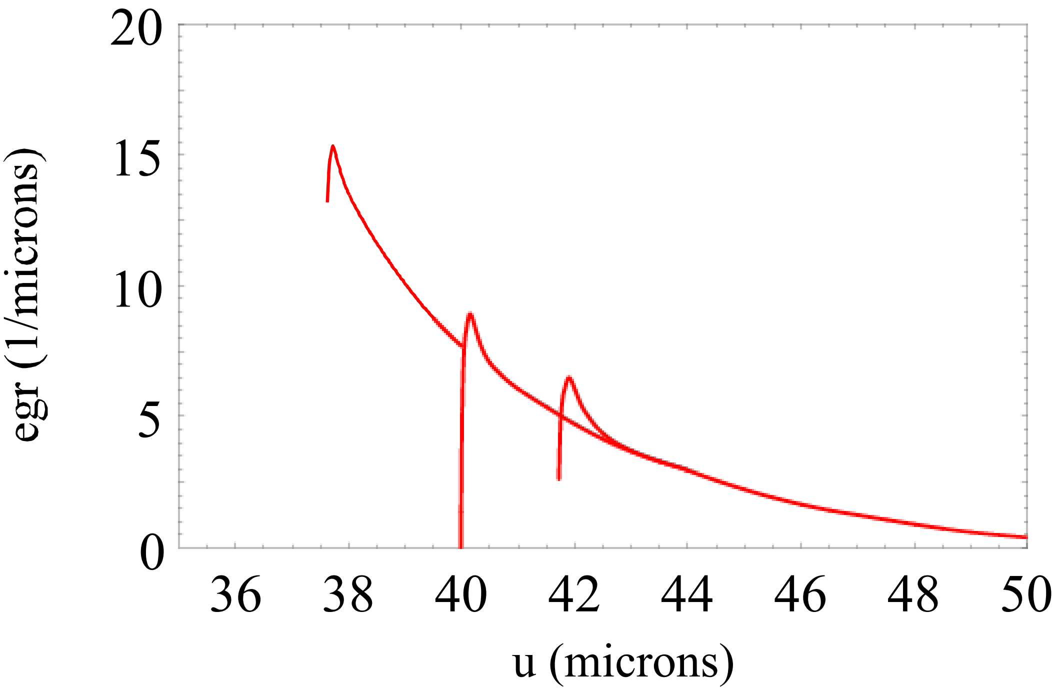

Fig 13 Exponential growth rate vs u, uo= 50, 44 and 40 microns

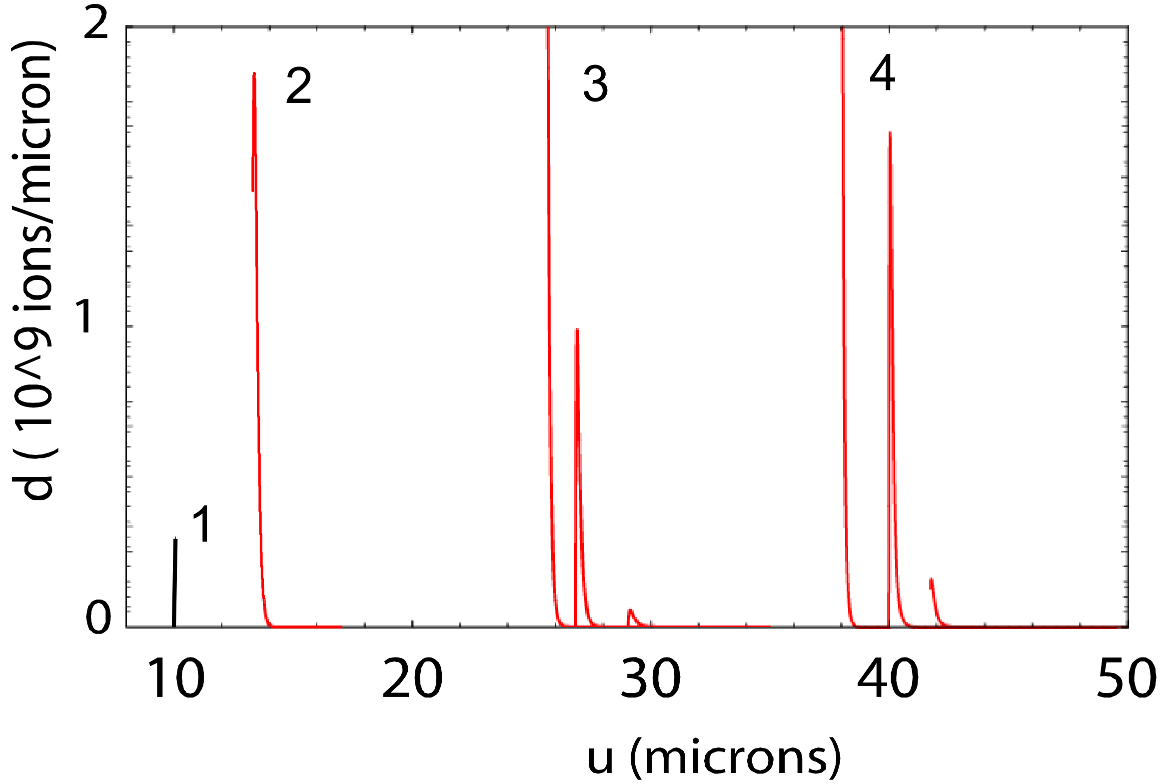

Fig 14 Overlay of line density for initial charge
and three sets of avalanches